Mixed Layer Response to Monsoonal Surface Forcing in the Arabian Sea

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LONG-TERM GOALS

Our long-range scientific objective is to observe and understand the temporal and spatial variability of the upper ocean and to identify the role of air-sea interaction in determining that variability. We seek to do this over a wide range of environmental conditions in order to improve our understanding of upper ocean dynamics and of the physical processes that determine the vertical and horizontal structure of the upper ocean.

OBJECTIVES

Prior to the Arabian Sea Mixed Layer Dynamics Experiment, efforts to understand air-sea interaction and upper ocean variability had never been done in a region characterized by strong, sustained forcing; and the separation of oceanic variability due to atmospheric forcing from that associated with mesoscale variability has been difficult. The combination of strong, sustained monsoonal forcing and mesoscale variability associated with eddies and coastal jets characteristic of the Arabian Sea presented a unique opportunity to add to our understanding of the upper ocean response to atmospheric forcing.

Objectives of the field experiment were to test these ideas: the upper ocean physical and biological response are largely one-dimensional; Ekman pumping velocities significantly affect the mixed layer evolution; summer mixed layer cooling results from one or a combination of increased cloud cover, large latent heat loss, lateral advection of coastally-upwelled water, open-ocean upwelling, and entrainment; entrainment is dominated by shears associated with sub-inertial wind-driven flow; and mesoscale variability provides the primary source of vertical circulation at the base of the mixed layer.

In this continuing work, our objective is to additionally test the following hypotheses: (1) three-dimensional flow divergences due to high-frequency and small spatial structure in the wind field are important in the vertical velocity field at the base of the mixed layer, (2) diurnal cycling during the NE monsoon produces a horizontally homogeneous mixed layer, (3) resolution of high frequency wind and diurnal heat forcing significantly modifies the large-scale heat transport, and (4) additional upwelling and vertical mixing associated with the mesoscale contributes significantly to the evolution of the mixed layer.

APPROACH

As a part of the ONR-sponsored Arabian Sea Mixed Layer Dynamics experiment we deployed an array of surface and subsurface mooring in cooperation with Rudnick (SIO), Eriksen (UW), Dickey (USC), and Marra (LDEO), from October 1994 - October 1995, just south of the climatological maximum of the Findlater jet in the north-central Arabian Sea. The observations showed that there were errors in some widely used flux climatologies, and showed striking differences in the surface forcing between the NE monsoon (November-January), characterized by moderate wind forcing and strong oceanic surface heat and freshwater loss, and the SW monsoon (June-August), with strong winds, significant oceanic heat gain, and reduced evaporation. The mixed layer was observed to cool and deepen during each monsoon, driven primarily by convection during the NE monsoon and wind-driven mixing during the SW monsoon. Mesoscale variability was the major signal in the velocity record, and provided significant horizontal heat fluxes.

The continuing work has two major thrusts. First, quantitative descriptions of the upper ocean response are being developed, including heat budgets and identification of the relative roles of various mixing processes. Second, we are using one- and three-dimensional models to test our understanding of the response at the site of the moored array and to extend it to the entire Arabian Sea.

Graduate student Albert Fischer (MIT/WHOI Joint Program) is completing his Ph.D. work on this material, working with Weller as advisor.

WORK COMPLETED

The field program provided an unprecedented look at the response of the mixed layer to the wide range of surface forcing found to be associated with the annual cycle in the Arabian Sea. Scientific analyses and publication are in progress. The effort has focused on integrating data to examine the mesoscale horizontal heat flux and investigating the effect of the diurnal cycle on the mixed layer in one- and three-dimensional models.

A quantified analysis of the upper ocean heat budget at the moored array has been completed. Additional datasets of combined TOPEX/ERS altimetry (courtesy of Leben and Fox, CCAR), satellite sea surface temperature (SST) (JPL), and SeaSoar surveys (Lee, UW/APL) have allowed identification of the dynamic origins of the strong horizontal heat fluxes observed. This work is described in a paper nearing completion, which will submitted accompanied by an overview paper of the oceanic response to the surface forcing already described in [*Weller et al*., 1998].

The three-dimensional model of [*McCreary et al.*, 1993] (referred to as MKM, see also [*McCreary and Kohler*, 1998]) has been used to investigate the Arabian Sea response to diurnal variability in the solar heat flux. Parallel runs of diurnally-varying and mean surface heat flux have been generated and are being analyzed.

To further examine how the diurnal cycle affect the vertical mixing and redistribution of heat, a series of idealized one-dimensional PWP mixed layer model [*Price et al.*, 1986] runs was undertaken, under a wide variety of surface forcing conditions. Analysis of these runs continues.

A collaboration with Craig Lee (UW/APL) used climatological data supplied by Simon Josey (SOC) to examine the relative effect of Ekman pumping and locally-driven entrainment on the deepening of the mixed layer across the Arabian Sea. This work is in press [*Lee et al.*, 1999].

RESULTS

Strong horizontal advection of water during the SW monsoon, seen in the heat budget of the moored array, was identified using satellite SST imagery and altimetry as being upwelled water from the Omani coast, transported by a filament (Figure 1). The timing of the filament arrival at the mooring site in the imagery coincided with the record of horizontal advection from the array. The sea surface height record from altimetry and the dynamic height computed from the WHOI moored record compared well, with a correlation coefficient of 0.85. During the NE monsoon, strong horizontal heat advection at the moored array was found to be associated with mesoscale eddies that had been generated in the previous SW monsoon and propagated westward. The altimetric record shows that mesoscale activity is most pronounced in the vicinity of the Somali Current and along the coast of the Arabian Peninsula.

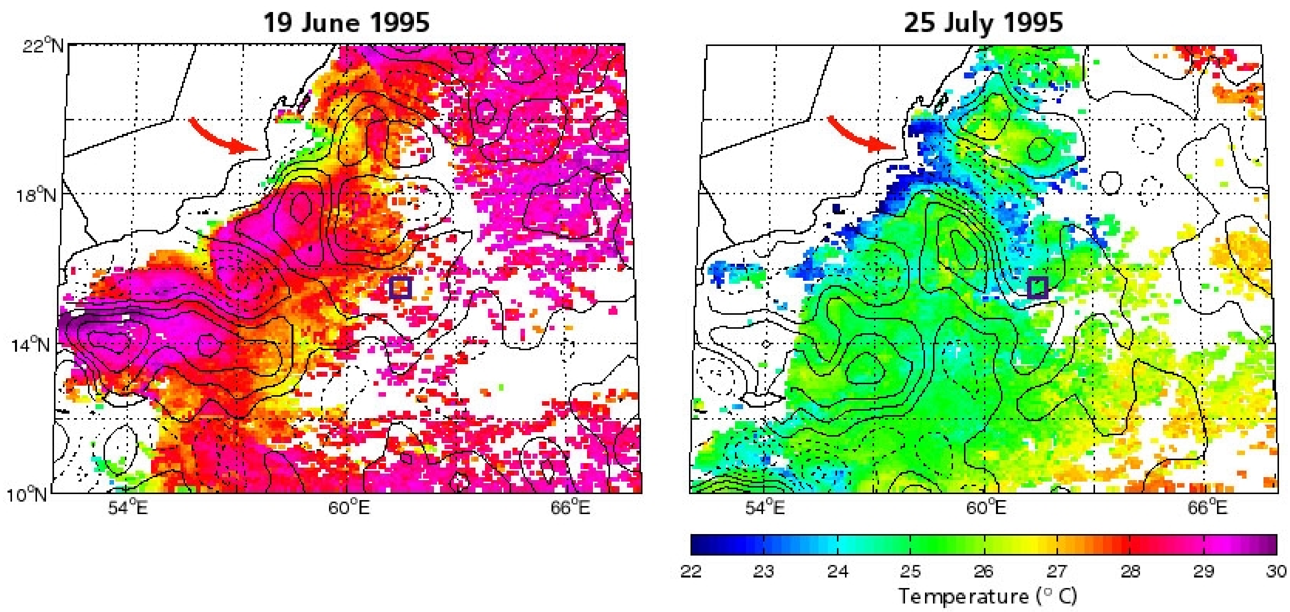

Figure 1: Maps of superimposed satellite-derived SST (color) and combined TOPEX/ERS altimetry (contours every 5 cm, solid lines positive and dashed negative) during the 1995 SW monsoon. Wind-driven coastal upwelling can be seen along the Arabian coast, and the development of a filament off Ras al Madraka (red arrow) exports cold water well into the interior of the Arabian Sea, leading to a strong horizontal heat flux at the site of the moored array (gray box), 600 km offshore.

Work with the three-dimensional MKM model has shown that diurnal forcing in the heat flux changes patterns of SST, mixed layer depth (MLD), as well as the heat storage (and transport) in the model through changes in the net vertical mixing. After a five-year spinup with monthly mean surface forcing, the model was run in two parallel runs for an additional five years, one with diurnally-varying solar heat flux, one with the monthly mean solar heat flux. The general circulation of each run is consistent with previous results, but variations in the mixed layer temperature and depth are seen. The diurnally-forced run has a cooler SST, and generally deeper mixed layers than the mean-forced run. The sensible and latent heat fluxes are calculated within the model, yielding a net surface heat flux which was larger into the ocean over the Arabian Sea in the diurnally-forced run. The closed basin of the Arabian Sea and the strong net surface heat flux into the upper layers of the ocean over the year lead to an export of heat through Ekman transport and advection across the southern boundary and entrainment into deeper layers. The additional heating in the diurnally-forced run should change the net heat transport out of the basin, this is under investigation.

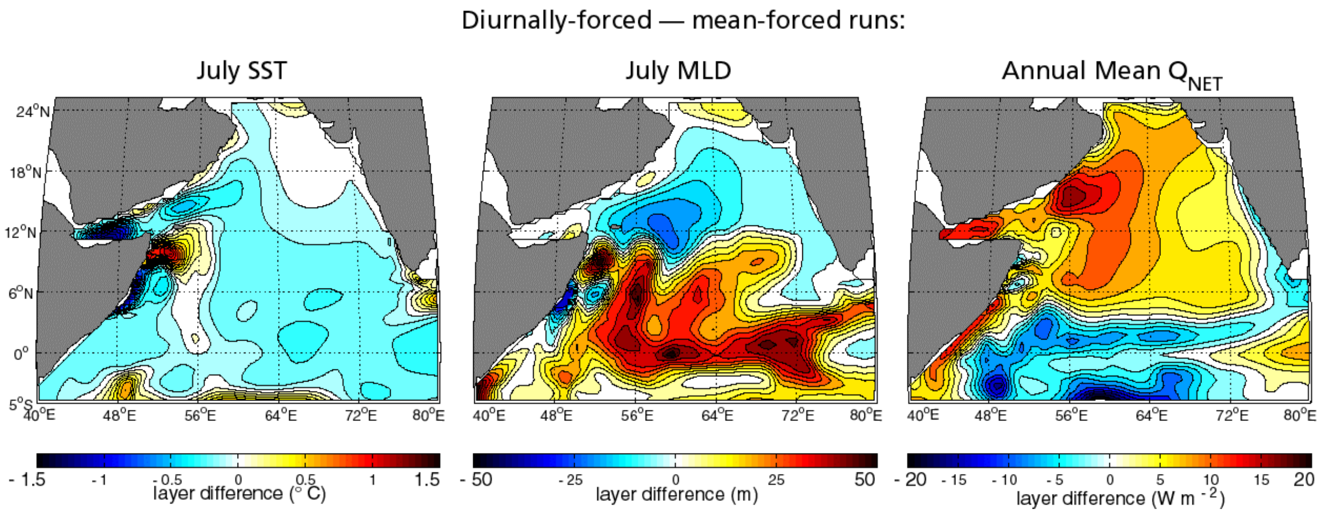

Figure 2: Differences of MKM model runs with diurnally-varying and mean solar heat forcing after five years. The first two panels are July SST and MLD. Over most of the basin the diurnally-forced run is cooler, while the effect on daily maximum MLD is mixed. The last panel is the annual mean net surface heat flux which is increased into the ocean over the entire Arabian Sea in the diurnally-forced run.

The additional vertical mixing caused by a resolved wind stress field has been studied ([*Large et al.*, 1991]; [*Chen et al.*, 1999]), and can be understood simply based on energetic arguments. While noted before [*Sui et al.*, 1997], the net effect of the diurnal cycle on SST and MLD has not been studied systematically, and cannot be understood as simply. The rectification of the diurnal cycle has been explored across a wide parameter space in net heat and wind forcing using the one-dimensional PWP model. The diurnal cycle rectifies into net cooling and deepening of the mixed layer when the net heat flux is positive, and is dependent on the strength of the wind (Figure 3). There is a significant effect on SST and mixed layer temperature only when the net daily heat flux is positive, although the lack of penetrative convection in the PWP model may be a factor. The daily maximum MLD is usually deeper in the diurnally-forced case, and always during high wind conditions. The validity of these conclusions may be strongly model-dependent, and further experiments with both simpler (Kraus-Turner type) and more complex (the KPP model of [*Large et al.*, 1994]) mixed layer models are planned.

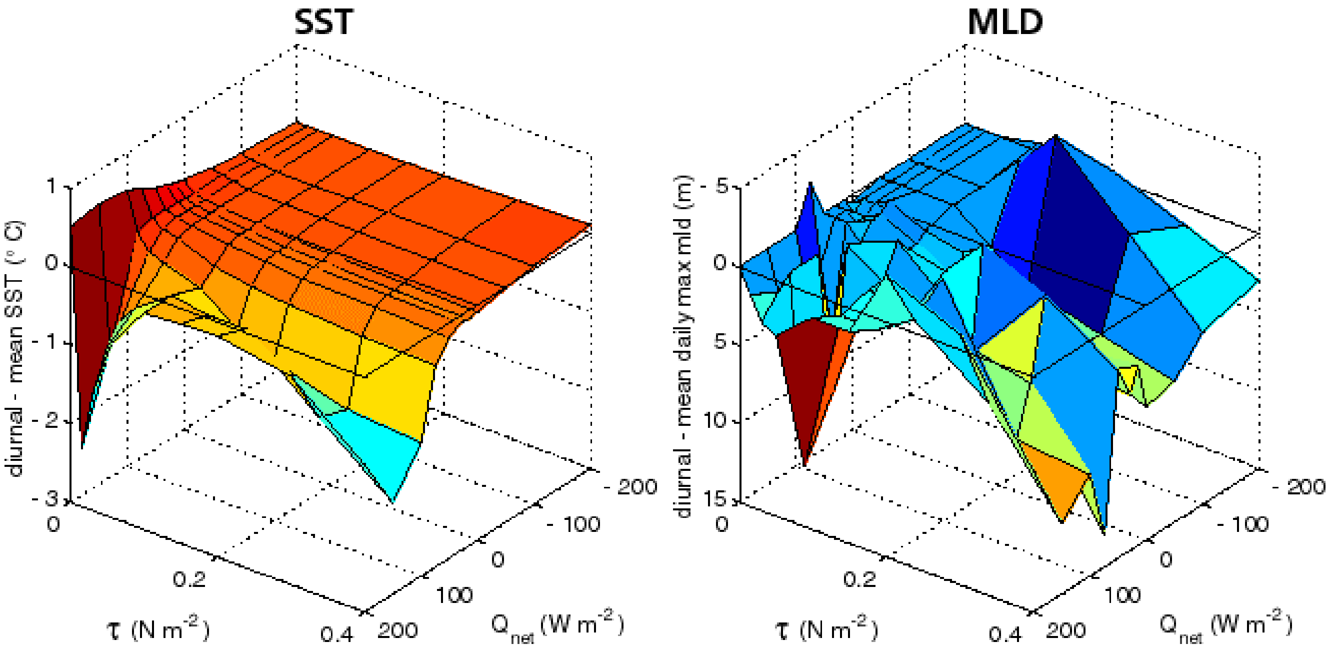

Figure 3: A summary of the differences in SST and maximum MLD in diurnally-forced and mean-forced 60-day runs of the PWP model, varying the net surface heat forcing and the wind forcing. Significant differences in SST only occur for net heating.

IMPACT/APPLICATIONS

The field work produced the first long time series of high quality near-surface meteorology and air-sea fluxes to be obtained in the Arabian Sea. Comparisons with climatology give us confidence in selecting forcing products for ocean models. Observations of the strong cooling heat flux associated with offshore transport give insight into the dynamic mechanisms connecting coastal upwelling and upper ocean cooling. The net effect of the diurnal cycle on the vertical mixing of temperature and on larger-scale circulation changes will be applicable to any modeling study of upper ocean circulation or biology, particularly in regions where mixed-layer diurnal variability is important. The large-scale model will yield additional information about the meridional heat flux in the Indian Ocean.

TRANSITIONS

Ongoing cooperation with Kindle (NRL) in modeling may lead to improvement of Navy ocean forecasting models in the region, and has led to confirmation of the quality of FNMOC model winds.

RELATED PROJECTS

This work has resulted in ongoing cooperative projects with numerical modeling (McCreary, SOEST; Kindle, NRL), satellite remote sensing (Leben, Fox, CCAR; Arnone, NRL), as well as with other ONR Arabian Sea investigators (Lee, Brink, Eriksen, Rudnick, Dickey, Marra). The role of mesoscale eddies in pulses in productivity has been investigated with the aforementioned ONR investigators as well as JGOFS Arabian Sea investigators (Honjo, WHOI; Prell, Brown; Dymond, OSU)

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